Collaboration Between a Robotic Bed and a Mobile Manipulator May Improve Physical Assistance for People with Disabilities

Ariel Kapusta*, Yash Chitalia, Daehyung Park, and Charles C. Kemp

***Abstract*— We present a robotic system designed to provide physical assistance to a person in bed. The system consists of a robotic bed (Autobed) and a mobile manipulator (PR2) that work together. The 3 degree-of-freedom (DoF) robotic bed moves the person's body and uses a pressure sensing mat to estimate the body's position. The mobile manipulator positions itself with respect to the bed and compliantly moves a lightweight object with one of its 7-DoF arms. The system optimizes its motions with respect to a task model and a model of the human's body. The user provides high-level supervision to the system via a web-based interface. We first evaluated the ability of the robotic bed to estimate the location of the head of a person in a supine configuration via a study with 7 able-bodied participants. This estimation was robust to bedding, including a pillow under the person's head. We then evaluated the ability of the full system to autonomously reach task-relevant poses on a medical mannequin placed in a supine position on the bed. We found that the robotic bed's motion and perception each improved the overall system's performance. Our results suggest that this type of multi-robot system could more effectively bring objects to desired locations with respect to the user's body than a mobile manipulator working alone. This may in turn lead to improved physical assistance for people with disabilities at home and in healthcare facilities, since many assistive tasks involve an object being moved with respect to a person's body.**

I. Introduction

Many people with disabilities could potentially benefit from robotic assistance with activities of daily living (ADLs), such as feeding and hygiene. General-purpose mobile manipulators have the potential to provide assistance with a variety of tasks to diverse users [1]. In this paper, we present evidence that mobile manipulators could provide better assistance by collaborating with robotic beds. In particular, we present a system that takes advantage of the complementary capabilities of a mobile manipulator (PR2) and a robotic bed (Autobed) for both perception and action.

Dental hygienists, barbers, and other professionals who perform tasks around the human body sometimes position peoples' bodies using adjustable furniture. By doing so, the professional can improve ergonomics and the quality of the services they perform. The two robots in our system coordinate in an analogous manner. Our system jointly optimizes the complementary actions of the robotic bed and the mobile manipulator with respect to task models and a model of the person. The robotic bed moves the person's body, which is a large payload, but does so slowly and infrequently with only a few degrees of freedom (DoF). The mobile manipulator then dexterously moves lightweight objects with

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Fig. 1: Using this system, the PR2 and Autobed configured themselves for the *wiping mouth* task. The system raised Autobed so the PR2 base could fit underneath.

respect to the person's body using a large number of degrees of freedom. For example, the PR2 in our system uses its 3-DoF mobile base, a 1-DoF telescoping spine, and a 7-DoF arm.

The robotic bed and the mobile manipulator also collaborate to achieve better perception of the human body. Most notably, the robotic bed uses tactile sensing to estimate the pose of the person's body. This is particularly advantageous, since the person's body will often be covered with bedding and hence challenging to observe with conventional line-of-sight sensors. Moreover, the pressure sensing mat we use in our system has a consistent view of the person in the bed and can readily ascertain if a person is currently in the bed.

We consider the robotic bed we have developed (Autobed) to be a true robot. It has sensors, actuators, models of itself, and uses ROS (Robot Operating System). This is related to efforts to make everyday devices smarter and enable them to coordinate with one another, such as the internet of things (IoT). Future assistive robots may operate in environments containing other devices with which they can collaborate for perception and action, including robotic wheelchairs and home appliances.

A. Related Work

1) Assistive Robots: Many researchers have long explored the idea of assistive robots, especially for people with motor impairments [2], [3]. The field of surgical robotics, particularly its use of multiple robot arms in collaboration, shares many similarities to our work [4]. Some surgical robots feature collaboration between heterogeneous robots, such as robotic surgical arms and a robotic surgical table [5], [6]. Other researchers have worked towards mobile manipulators as platforms to provide mobile assistance [7]–[12], primarily with manipulation tasks.

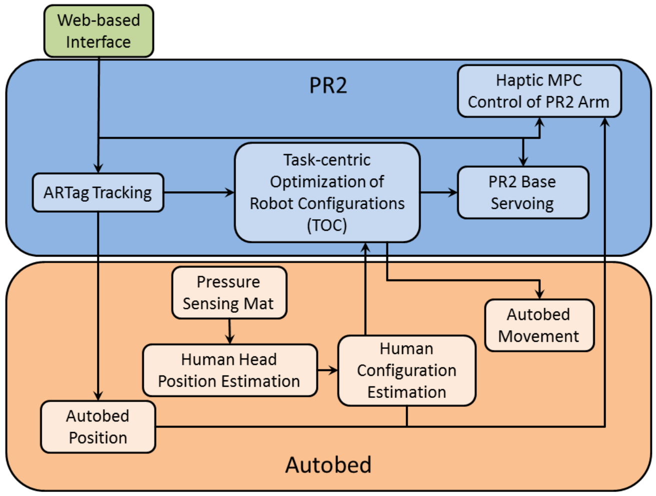

Fig. 2: Block diagram of the system architecture

We focus on getting a mobile manipulator into a configuration where it can effectively provide assistance. Much prior research has investigated how to find good configurations for a mobile robot. Many are based on the reachability map presented by Zacharias et al. [13], such as [14]–[18]. Other methods to select configurations for robots include using data-driven simulation [19]–[21] and planning (e.g., RRTs) [22].

For the system we present in this paper, we have applied our previous work to a real PR2 and robotic bed [21], [23].

2) Collaborative Robots: Many investigations have explored multi-robot, collaborative systems [24], [25], including heterogeneous multi-robot or swarm systems [26], [27]. Our approach is similar, applying the idea of heterogeneous multi-robot collaboration to the field of assistive robotics.

3) Robotic Beds: Previously, several groups have worked on incorporating robotic technologies into hospital beds [28]–[31]. In this work, we have used Autobed as an agent in a collaborative heterogeneous multi-robot system.

4) Pose Estimation: A challenge in providing assistance with ADLs for a person in bed lies in perceiving the position and orientation of various body parts, which are often occluded by bedding. Several groups of researchers have used a model based approach to fit a 3D model to estimate the pose of a person lying on a mattress [32], [33]. Alternatively, Liu et al. used pictorial structures to identify the location of body parts of a person lying on a pressure sensing mat [34].

II. The System

As illustrated in Figure 2, our system integrates a number of components. The system uses the collaboration between two robots, a PR2 and Autobed, leveraging the strengths of each. We focus particularly on the physical and perceptual collaboration between the robots. With regard to physical collaboration, the PR2 has a mobile base, high dexterity, a high number of degrees of freedom, and low payload capacity arms. Complementing these capabilities, Autobed has no base mobility, a low number of degrees of freedom, and a high payload capacity. With respect to perceptual collaboration, the system uses the PR2's head-mounted Kinect v2 RGB-D camera to visually locate Autobed. It also uses Autobed's joint encoders and pressure mat to estimate the position and configuration of the bed and the human on the bed.

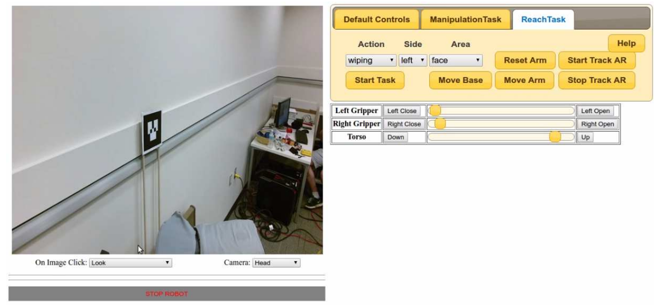

Fig. 3: The web-based interface to run the system. On the left is a video feed from the PR2's head-mounted Kinect v2 RGB-D camera. On the right are buttons to command the system to perform a desired task.

A. Web-based Interface

The user provides high-level supervision and input to the system through a web-based interface. The web-based interface (see Figure 3) is based on the interface from [35]. It has a custom set of options for performing the semi-autonomous actions to assist the user in performing the task, as well as the previously existing options to control the movements of the PR2 head and base.

B. Task-centric Optimization of Robot Configurations (TOC)

To select the configuration of the PR2 and Autobed from which to perform the requested task, our system uses Task-centric Optimization of robot Configurations (TOC) from [21] and [23].

TOC jointly optimizes two 6-DoF system configurations, each of which consists of a 4-DoF configuration for the PR2 (X-Y base position, base orientation, and Z-axis height) and a 2-DoF configuration for Autobed (Z-axis height and head-rest angle). TOC models each task as a sparse set of goal poses (position and orientation of the end effector). These task models could potentially be customized based on user preference. TOC runs the optimization for samples of the person's position on the bed, h_i, given robot, person, and environment models. The person model also could potentially be customized to better fit the user. TOC interprets the optimization results to see if a single system configuration is sufficient for the task, or if there is value in using two system configurations. It then associates the one or two system configurations with their respective h_i. TOC uses these associations to approximate a function that it uses at run-time to select system configurations, given the observed person's position on the bed. Figure 4 shows the simulation environment used by TOC, demonstrating a configuration for the *wiping mouth* task.

C. Autobed

We have modified a standard electric hospital bed from Invacare into a robot we have named Autobed. Our modifications extend our previous work [36]. By adding additional hardware between the remote control and the bed's motor drivers, we are able to send commands directly to the bed

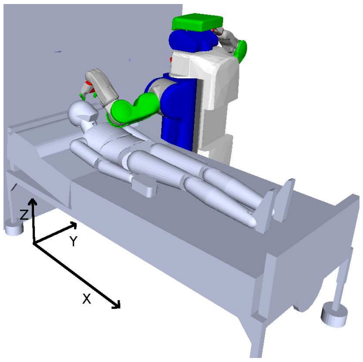

Fig. 4: The simulation environment used by TOC, our system's configuration selection method. A wall is behind the bed.

using a Robot Operating System (ROS) interface. We run most of Autobed's functions on a Raspberry Pi single-board computer attached to the bed.

1) Autobed Configuration: We use accelerometers to measure the angle of the bed's head rest and leg rest. We mounted a Kinect v1 to the footboard of Autobed, pointing at an ARTag on the floor to measure the height of the bed. Autobed runs as a robot in ROS with a model of itself. It communicates its configuration and model through ROS in real-time.

2) Autobed Movement: Autobed's actuators are capable of changing the height of the bed, the angle of the head rest, and the angle of the leg rest when a human is lying on the mattress. The Raspberry Pi runs a bang-bang controller with a deadband to reach commanded configurations.

3) Human Head Position Estimation: We have equipped Autobed with a pressure sensing mat, manufactured by Boditrak (`http://www.boditrak.com/` Model #: BT3510), to measure the pressure distribution of the person lying on the bed. We placed the pressure mat on the top side of the mattress and below a fitted sheet. Our system runs the head position estimation on an external computer at 5Hz. The pressure mat returns a pressure value for each of its 1728 tactile pixels (taxels). Autobed sums the pressure values to estimate the total weight on the pressure mat. When this estimate exceeds a threshold, it reports that the bed is occupied.

Autobed uses a determinant of hessian (DoH) [37] blob detector from scikit-image (`http://scikit-image.org/`) to estimate the 2D position of the head on the pressure mat. Because the location of the head is near the top of the bed, the blob detector is weighted with a prior that prefers head-sized blobs in the top 20% of the pressure matrix. On average, the head position estimation algorithm takes $\sim$8 milliseconds to run, with a maximum execution time of $\sim$18 milliseconds on an external machine (Intel Core 2, 2.53 GHz). Figure 5 shows the estimated head position for a person lying on Autobed.

4) Human Configuration Estimation: Based on the estimated human head position and on Autobed's joint configuration, Autobed estimates the configuration of the human on the bed. The system assumes the human is lying on the bed parallel to the long edge of the bed (X-axis), with arms at its sides and its legs mostly straight. Figure 4 shows the simulation environment with an example bed and human configuration.

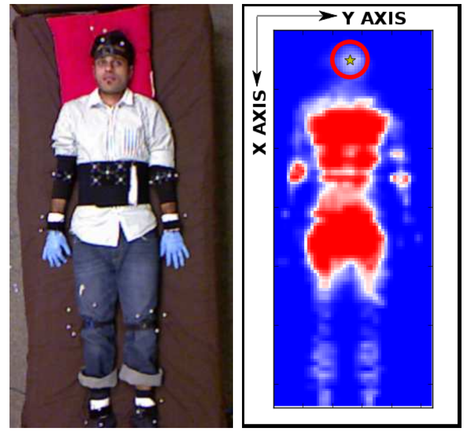

Fig. 5: Left: View of a participant wearing various infrared reflective markers lying on Autobed. Right: Visualization of the pressure mat measurements from the participant with the estimated head position marked by a star inside a circle.

D. PR2

Our system uses a PR2 robot, a general-purpose mobile manipulator from Willow Garage that was not specifically designed as an assistive device. The PR2 has a mobile base, two 7-DoF arms with grippers, a pan-tilt head, and a head-mounted Kinect v2. The arms have high dexterity, but a low payload capacity of 1.8 kg.

1) ARTag Tracking: Our system uses the code package ar_track_alvar (`http://wiki.ros.org/ar_track_alvar`) to track an ARTag mounted on the back of Autobed, and thereby to locate Autobed. The PR2 moves its head to keep the ARTag in the center of its head-mounted Kinect's view as the PR2 moves around.

2) Haptic MPC Control of PR2 Arm: To perform movements with the PR2's arm, our system uses a newer version of the model predictive controller described in [38], with low stiffness. Note that our current system does not use the fabric-based skin or tactile sensing from that work. Our system uses this controller to move the PR2's arm to end effector poses (position and orientation) or joint configurations (when resetting the arm configuration between trials).

3) PR2 Base Servoing: The system uses the ARTag servoing from [35] to move the PR2 base to a position and orientation from TOC, defined with respect to Autobed's ARTag. Servoing moves the PR2 directly from its current position to the goal position, so the current system requires that the PR2 have a straight-line, unobstructed path to its goal position (e.g., the PR2 must be on the correct side of the bed).

III. Evaluation

We performed tests to provide evidence for the benefits of our system and approach.

A. Implementation Details

We included into TOC's environment model a wall behind the bed (see Figure 4), which matches our test environment. We roughly modeled the geometries of the bed. We expanded the bed model by a few centimeters to decrease the chance of collision between the PR2 and Autobed, thereby providing a margin of safety.

For each trial, we started the PR2 on the same side of the bed as the goal position. The PR2 remained connected by wire for power and communications during each trial. In the case when TOC chose to use two configurations for the task, the experimenters ran the system for each configuration separately, starting the PR2 on the appropriate side of Autobed.

In our experiments we used a weighted medical mannequin. Although the mannequin's overall weight is similar to that of a human (∼48 kg), the weight is mostly located in the torso, resulting in a pressure profile that differs from that of a human. We added 4.5 kg of weights to the mannequin's head to better simulate a human's pressure profile (an average human head weighs ∼4.5 kg). To reduce noise in the estimated head position when running the human head position estimator, we applied a median filter with a 30 element (∼6 seconds) sliding window. In our experiments, the system only considers translations of the mannequin on the bed in the Y direction (the direction of the width of the bed, as shown in Figure 5 Right).

Throughout our experiments, the PR2 used its left arm to perform the task and kept its right arm raised and to its side, out of the way.

B. Head Position Estimation Tests

We conducted a study with 7 people (N = 7) to evaluate the performance of our method of head position estimation. We conducted this research with approval from the Georgia Institute of Technology Institutional Review Board (IRB), and obtained informed consent from all participants according to our experimental protocol.

We required that participants meet the following inclusion/exclusion criteria: ≥18 years of age; have not been diagnosed with ALS or other forms of motor impairments; and fluent in written and spoken English. Their weights ranged from 52 to 95 kg and their heights ranged from 160 to 187 cm. For the experiment, we placed Autobed in a room equipped with 14 motion capture cameras. We asked the participants to lie on Autobed in a supine configuration comfortable to them, keeping their heads looking straight, while wearing various infrared reflective marker arrays on their bodies and heads (see Figure 5 Left). We designated the projection of the center of the forehead marker array onto the plane of the bed as the ground truth head position.

Fig. 6: The starting configuration of the PR2 and Autobed before a trial, with the PR2 starting on the left side and right side of Autobed.

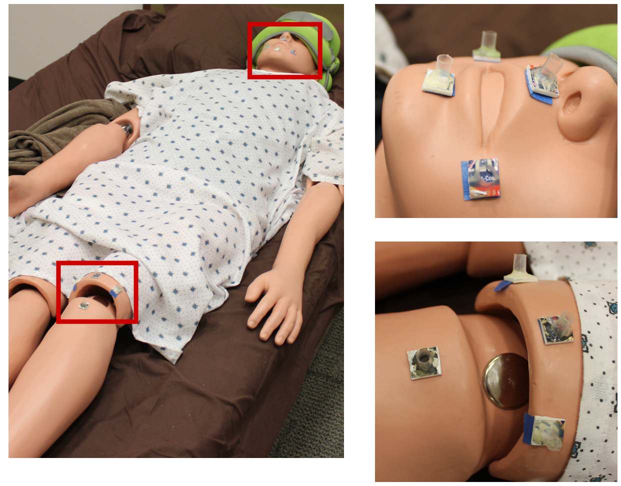

Fig. 7: Left: Mannequin on Autobed with task areas highlighted with a red rectangle. Right: The physical 5-DoF goals, hollow tubes affixed to the mannequin, for the *wiping mouth* task and the *scratching left knee* task.

We randomly selected 30 pressure distribution images from each participant while they were lying on the bed looking straight to form our test dataset of (210 total pressure distribution images). We compared the estimated head position with ground truth.

Figure 5 Right shows the estimated head position for a pressure image. The mean and standard deviation of the magnitude of the error were 2.45 cm and 1.24 cm, respectively. The mean and standard deviation of the error in the Y direction were 1.52 cm and 1.07 cm, respectively. The mean and standard deviation of the error in the X direction were 1.48 cm and 1.38 cm, respectively.

C. PR2 and Autobed Collaboration Tests

We performed a series of trials to investigate the effectiveness of our system at getting the PR2 and Autobed to a set of configurations from which the PR2 could perform a desired task. Specifically, for each task and for a mannequin in different locations on the bed, we examined the percentage of goal poses the PR2 could reach on the mannequin.

1) Experimental Protocol: An able-bodied experimenter sitting at a nearby desk used the web-based interface to simulate performing two tasks on a medical mannequin lying

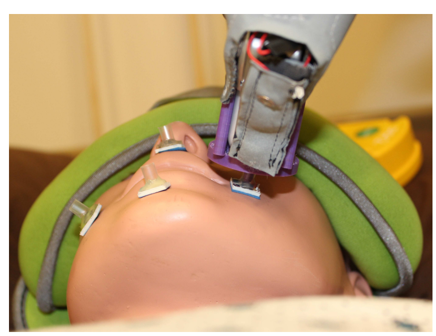

Fig. 8: Example of the PR2 successfully reaching a goal pose for the *wiping mouth* task. The PR2 is holding a small tool ending with a solid cylinder which we manually inserted into the goal tubes on the mannequin.

TABLE I: Using the system to configure the PR2 and Autobed, the PR2 could reach all goal poses (out of 4) using one configuration for both tasks. For some trials, the system used more configurations or could not reach all goal poses when Autobed's movement or perception were not used.

		Full System		No Bed Movement		No Position Estimation	
Task	Y-Direction Shift of Body (cm)	% Reached	# Configs	% Reached	# Configs	% Reached	# Configs
Wiping Mouth	-15	100	1	100	1	100	1
	0	100	1	100	**2**	N/A	N/A
	15	100	1	100	1	100	1
Scratching Left Knee	-15	100	1	100	**2**	**75**	1
	0	100	1	100	1	N/A	N/A
	15	100	1	**75**	1	100	1

on Autobed. The tasks were scratching the left knee and wiping the mouth. Previous work has noted that these two tasks may be useful for those with severe motor impairments [1].

We started the experiments with the PR2 $\sim$1 m away and facing Autobed (see Figure 6). Using the web-based interface, the experimenter moved the PR2's head to put Autobed's ARTag in the PR2's head-mounted Kinect's field of view. Afterwards, the experimenter commanded the PR2 to begin tracking and following the ARTag. The PR2 locates Autobed based on the ARTag pose. The experimenter then initiated the task with the interface. The system used TOC to select and move to one or two configurations for the PR2 and Autobed for the task, based on the estimated position of the mannequin. The PR2 then adjusted its height as Autobed adjusted its height and head-rest angle. Once the PR2 and Autobed completed those configuration adjustments, the experimenter commanded the PR2 to autonomously move its base to the position and orientation selected by TOC. Once the PR2 finished moving into position and upon receiving a command from the experimenter, the PR2 moved its left end effector to the task area. Figure 1 shows a configuration reached using the system for the *mouth wiping* task with the mannequin on the left side of the bed.

At this point in the experiment, the experimenter pressed the PR2's emergency-stop button and manually moved its left end effector to each of 4 task-specific goal poses around the task area. We affixed a hollow small plastic tube to the mannequin at each goal location. The PR2 held a small tool with a small solid cylinder in its left end effector. If the experimenter could insert the PR2's held cylinder into a goal tube without the cylinder touching the sides of the tube, we considered the PR2 as being able to reach that goal (see Figure 8). Note that the PR2 has infinite-roll wrists making the goal poses 5-DoF.

For the scratching left knee task, the goals were 4 cm to the left and right of the knee, and 2.5 cm above and below the knee. For the mouth wiping task, the goals were to the 3.5 cm to the left and right of the mouth, and 2 cm above and below the mouth. The goal locations are shown in Figure 7. Table I shows the percentage of reachable goal poses for each task as we translated the mannequin from the center of the bed in the Y direction by -15, 0, and 15 cm. We also reported the number of configurations used by the system.

2) Overall Collaboration: Using all parts of the system, the PR2 was able to reach all goal poses on the mannequin from a single configuration.

3) Physical Collaboration: The two robots collaborate physically to allow the PR2 to better perform the task, by adjusting the Autobed configuration to give the PR2 better physical access around the mannequin and to adjust the mannequin's configuration. A solution frequently used by the system to reach parts of the mannequin on the bed was to raise the bed and to move the PR2's base under it.

To evaluate the value of physical collaboration between the two robots, we examined the PR2's ability to reach the task-specific goal poses if Autobed were fixed in its lowest, flattest configuration. Without physical collaboration between the two robots, the PR2 could not reach all goals for all tested positions of the mannequin on the bed and required two configurations (one on each side of the bed), instead of one, to reach all goals for some positions of the mannequin on the bed.

4) Perceptual Collaboration: The two robots collaborate perceptually to estimate the mannequin's position and configuration, allowing better selection of an initial configuration for the task.

To evaluate the value of the perceptual collaboration, we examined the PR2's ability to reach the goal poses if the system falsely assumed the mannequin was in the center of the bed. In this test, the experimenters only tested with the mannequin translated -15 cm and 15 cm in the Y direction because with the mannequin in the center of the bed, the system's assumption of the mannequin's position would be correct. Without perceptual collaboration between the two robots, the PR2 could not reach all goals for all tested positions of the mannequin on the bed.

Additionally, our system uses perceptual collaboration to inform the PR2 when autonomously moving its end effector to the task area. Without perceptual collaboration the PR2 in our system may have an inaccurate estimation of the task area.

IV. CONCLUSION

The system we have presented provides evidence for the benefits of the collaboration between a robotic bed and a mobile manipulator. A user provides high-level supervision for the system through a web-based interface,. The PR2 and Autobed then work together to reach task-relevant goal poses. The system uses physical and perceptual collaboration between the PR2 and Autobed, leveraging their respective strengths.

We found that Autobed's movement and perceptual capabilities each improved the overall system's performance.

Using the system to configure the PR2 and Autobed, the PR2 could reach all goal poses from one configuration for all tested tasks. We have provided evidence that collaboration between a robotic bed and a mobile manipulator may improve physical assistance for people with disabilities.

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